A Survey of Quadrotor Unmanned Aerial Vehicles

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Abstract— **In the past decade Unmanned Aerial Vehicles (UAVs) have become a topic of interest in many research organizations. UAVs are finding applications in various areas ranging from military applications to traffic surveillance. This paper is a survey for a certain kind of UAV called quadrotor or quadcopter. Researchers are frequently choosing quadrotors for their research because a quadrotor can accurately and efficiently perform tasks that would be of high risk for a human pilot to perform. This paper encompasses the dynamic models of a quadrotor and the different model-dependent and model-independent control techniques and their comparison. Recently, focus has shifted to designing autonomous quadrotors. A summary of the various localization and navigation techniques has been given. Lastly, the paper investigates the potential applications of quadrotors and their role in multi-agent systems.**

Keywords - quadrotor, review, autonomous control, vision systems, navigation.

I. INTRODUCTION

The quadrotor or quadcopter is a unique type of Unmanned Aerial Vehicle (UAV) which has Vertical Take Off and Landing (VTOL) ability. The quadrotor has an advantage of maneuverability due to its inherent dynamic nature. It is an under-actuated system with four inputs (roll, pitch, yaw and throttle) and six outputs. The parameters that determine the characteristics of a flying machine are the flying principle and propulsion mode [1], Figure 1 shows classification of different kind of aircrafts based on these parameters.

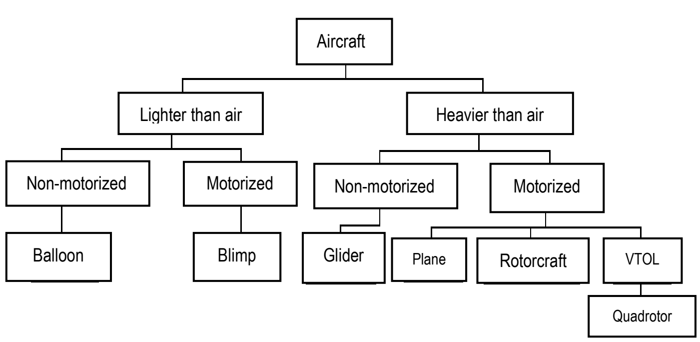

Fig.1. Aircraft classification depending on flying principle and propulsion mode

With developments in fields like sensor fabrication and automation, designing UAVs with different characteristics is becoming easier. UAVs were initially considered only for military applications, but as the cost to manufacture these flying robots decrease, users are finding civilian applications like traffic surveillance. A major advantage that a UAV has over manned aerial vehicles is that its flight time is restricted only by the fuel/battery life, whereas in manned vehicles the human component like fatigue has to be considered. They are also useful for missions and tasks which are beyond the limitations of human endurance.

II. MECHANISM OF FLYING

The major advantage of a quadrotor over a traditional helicopter is the fixed rotor propulsion mode. The roll, pitch and yaw of a quadrotor changes depending on the throttle in each rotor. The four rotors are aligned such that, the rotors on opposite ends rotate in the same direction and the other two in the opposite direction.

In order for the quadrotor to move about the roll axis, the throttles of the other side rotors (right or left) are increased, while reducing the same side rotor throttles. For movement about pitch axis, the front or back rotors are increased or reduced in the same way as for roll. In case of movement about the yaw axis, the counter-clockwise rotating rotors throttles are increased for rotation of the vehicle in counter-clockwise direction and the same holds good for clockwise rotation as well.

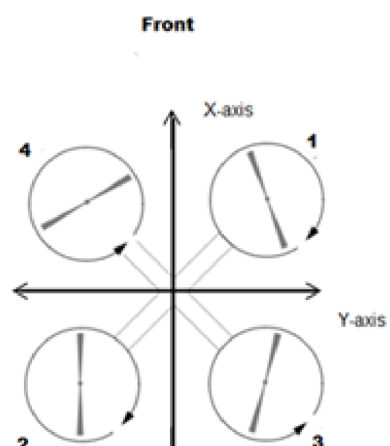

Fig.2. X-configuration

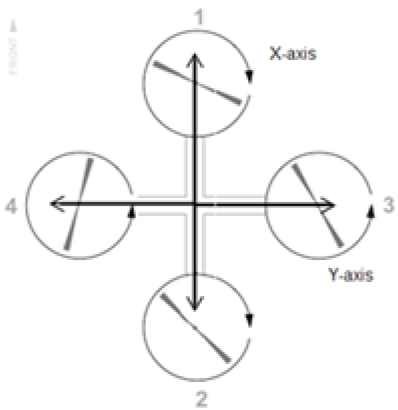

Fig 3 +- Configuration

The vehicle has two different configuration in which it can be flown, the 'X' configuration (Fig. 2) and the '+' configuration (Fig. 3). An X-configuration quadrotor is considered to be more stable compared to + configuration, which is a more acrobatic configuration. Figure 4 shows a typical quadrotor with the inertial measurement unit (IMU) sensors, the Electronic Speed Controllers (ESCs) and the microcontroller at the center and the four rotors at each end. The PING ultrasonic sensors were project specific.

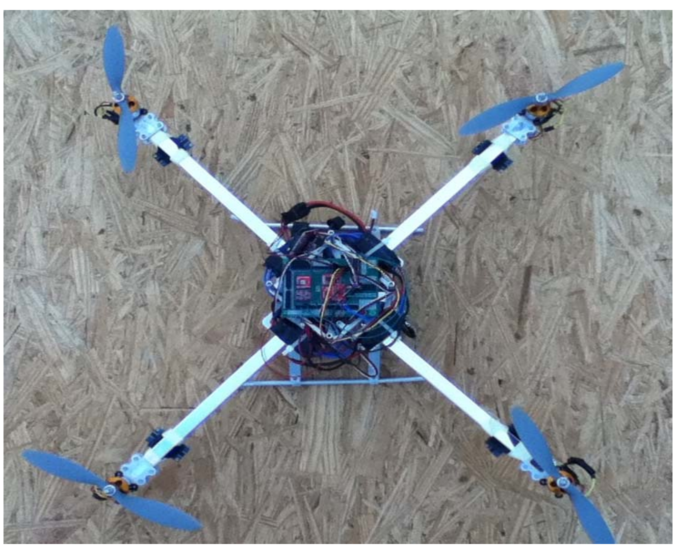

Fig. 4 Typical Quadrotor

III. CONTROL SYSTEMS AND DYNAMIC MODELS

With the increase in attention UAVs and quadrotors have received in the last decade, the algorithms laid out to control them have also increased substantially in number and complexity. Various control structures ranging from basic PID controllers [15, 27, 62] to more complex systems using backstepping or neural networks [16, 26, 46] have proved to be efficient.

There has been considerable innovation in the sensors that are used to control the quadrotor as well. Modern MEMS technology makes it easier to add more sensors on a small quadrotor as the space and weight constraints can be stringent. Sensors including basic IMUs, GPS modules and cameras have all been used in quadrotors.

The general method to design a control system is to calculate the dynamic model of the system. The dynamic model of a system is a mathematical equation that comprises of all the forces that can act on the system at a given time.

Many researchers have also tried comparing different control techniques [12, 14, 16, 67] and in most cases a quadrotor proved to be a dynamic vehicle with major challenges because of its under-actuated nature. Algorithms like PID, backstepping and feedback linearization have mainly been applied and proved to work well with a quadrotor.

A typical quadrotor will have parts like ESCs, four rotors, an IMU and a microcontroller running a control algorithm. Parts like vision based system and GPS are optional. As explained in Section I, the quadrotor is controlled using the values of its throttle, roll, pitch and yaw. The control algorithm reads the IMU sensor values and modifies these values in the opposite direction to stabilize the system.

While most research done till date is on mini-quadrotors, i.e. quadrotors that are small in size typically between 1 to 2kg, there have been a few papers that have tried researching on large scale quadrotors of up to 4kg [56]. The major difficulty that larger quadrotors face is that their weight causes the dynamics of the machine to change completely.

There have also been control methodologies which have found their motivation in nature [68]. Quadrotor control is based upon interactions of animals and insects in nature. The control algorithm is developed in a way that it can be used in a multi-agent environment, where each quadrotor can predict the location of the other. Control systems are also designed specifically for multi-agent systems [64, 68] where the quadrotors work along with each other to perform a specific task.

Another major difficulty that is faced in control of a quadrotor is forces of nature. Factors like wind and terrain play a very important factor when flying in an open space. Control systems [53] for these conditions are also performed where wind parameters are estimated and the different degrees of freedom are control based on these parameters

IV. SENSORS

This section describes the major sensors found on a quadrotor and the uses of each of them. The most basic and necessary sensor on any quadrotor is the IMU sensor [15, 16, 21, 26, 35, 72].

The IMU consists of an accelerometer and a gyroscope. Both these sensors are used in order to maintain the orientation of the quadrotor with respect to Earth. The accelerometer measures the orientation of the quadrotor with respect to earth. The reason why we need the gyroscope as well is because the accelerometer cannot sense rotation and only gives readings assuming the platform is stationary. The gyroscope has the ability to measure the rate of rotation around an axis, for example, if the quadrotor moves in its pitch axis the gyroscope value for the pitch axis will be a non-zero value until it stops the movement in the pitch axis.

Ultrasonic range sensors like the Ping sensor is another sensor that can be commonly found on a quadrotor; the major use of this sensor is for low level altitude control and obstacle avoidance. The sensor is generally used for quadrotors which need to hover at a certain height or need to fly in an indoor environment where it has to detect obstacles. The sensor need not necessarily be an ultrasonic sensor - it can also be an infrared or a Laser range finder which can measure distance [31, 35, 61].

Even though the IMU sensors help in calculating orientation of the vehicle, as time goes on very slight errors in the measurement of the acceleration can compound and result in significant errors in position and velocity. Therefore, some additional sensors can be added for increased stability and autonomy. The next most common sensor is a barometer for measuring altitude, and a magnetometer for measuring direction. Sensors from a Nintendo Wii Motion Plus and Nunchuk can also be used.

Another important sensor that can commonly be found on quadrotors is a GPS [35, 67]. The purpose of GPS is tracking and localization. In an outdoor environment it is important to realize the location of the quadrotor both for safety and because location gives other information, especially when the objective is to survey a certain region.

Apart from the sensors mentioned above, a camera is another highly used sensor on a quadrotor [1]. Apart from providing video feedback a camera can also be used for image recognition and processing as well as obstacle avoidance. A large number of researchers use it for various different applications on a quadrotor.

V. VISION SYSTEMS

Due to miniaturization of quadrotors use of on board LIDARs becomes impractical. For accurate position estimation and mapping researching are turning to vision sensor systems.

The vision systems implemented in UAVs cover areas such as object detection and object tracking, position estimation, navigation, obstacle detection, autonomous landing, and stable hovering among others. [8, 41, 49, 50, 58]

Visual servoing, also known as Vision-Based Robot Control, is a technique which uses feedback information extracted from a vision sensor to control the motion of a robot. Visual servo algorithms have been extensively developed for aerial robots in the last decade. [11, 18, 19, 22, 23, 25]

Visual servo techniques can be broadly classified into Image Based (IBVS) and Position Based (PBVS). PBVS is a model-based technique in which the pose of the object of interest is estimated with respect to the camera and then a command is issued to the robot controller, which in turn controls the robot. In this case the image features are extracted and are used to estimate 3D information. Hence it is servoing in 3D [7, 9, 54, 57, 58, 60, 72]. In IBVS the control law is based on the error between current and desired features on the image plane, and does not involve any estimate of the position of the target [11, 20, 33, 69].

Various types of input systems have been used for controlling the quadrotor in specific ways. Two major types of such systems are those employing on-board camera systems and those employing off-board camera systems. Monocular systems (single camera) use a single downward facing onboard camera as in [13]. Two camera systems have been employed for obtaining more accurate tracking results [5, 6] - they use one onboard camera and one pan tilt camera on the ground for obtaining better altitude measurements. Ground based external camera systems are used in tracking the quadrotor within specific field of flight [4]. A novel method of relative navigation using moiré patterns is presented in [63]. More recent research is seen to be concentrated towards using stereo cameras and 3D tracking. A system using a real time trinocular vision system to obtain 3D data is described in [48]. This data is then validated using onboard sensors.

For tracking the quadrotor from off board cameras most algorithms use blob detection. Four to five colored blobs are marked on the quadrotor and are used to calculate orientation and position [4, 5]. Other papers [22] have used direct feature detection from images of the quadrotor. One research group [44] uses the CAD model of the quadrotor for feature matching. Techniques like optical flow calculation are then applied to the extracted features for position estimation [3, 44].

To improve the resolution and control performance the data from camera can be integrated with or validated against other onboard sensors like IMU (multi sensory control) [48, 71]

VI. NAVIGATION

A. *Localization,Mapping and Planning*

For an autonomous robot the ability to move about in its environment and reach its desired goal location using the best feasible path is called navigation. Since quadrotors are often chosen for their mobility and maneuverability it is essential that the quadrotor incorporates a good navigation system. If the user provides a map of the environment it is called map-based navigation. If the UAV is expected to navigate in an unknown environment, the quadrotor needs to build a map and then calculate its own location within the map. This is called localization. This process needs to be done constantly as the robot moves through the map. Hence it is known as simultaneous localization and mapping (SLAM) [13, 45].

B. *Algorithms*

Due to the limited on-board capability of quadrotors, the navigation algorithms are run on an off-board remote computer. These algorithms take date from the primary sensors and estimate position, calculate path and send control commands to the quadrotor [24, 34]. The main difference for navigation algorithms for quadrotors is that all mapping and path planning have to be done in a 3D co-ordinate system (since altitude also must be taken into consideration).

Quadrotors that use vision sensors as their primary sensors use VSLAM or Visual SLAM [10].

The control algorithms are often implemented in integrated loop with highest level algorithm running in the innermost most. For safe testing a basic obstacle avoidance algorithm runs as the outer loop [3].

C. Testbeds

For extensive testing of the various control algorithms that are being developed efforts are being taken to develop a robust testbed. The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control or STARMAC is one example of an outdoor testbed. It comprises a set of autonomous quadrotor helicopters that can follow prescribed waypoint trajectories [36, 66]. Real-time Indoor Autonomous Vehicle Test environment or RAVEN is another testbed designed to explore long duration autonomous air operation using multiple UAVs [39, 65].

Some similar developments are studied in [40, 51, 67].

VII. APPLICATIONS

Due to some unique abilities of the quadrotor such as high maneuverability, small size, and easy control quadrotors are finding many applications. The most significant of them would have to be search-and-rescue and emergency response. Other major applications of quadrotors are in homeland security, military surveillance, and search and destroy. Miniaturization of quadrotors has enabled them to be used for border patrol and surveillance. Quadrotors also have potential applications in other areas like earth sciences where they can be used to study climate change, glacier dynamics, and volcanic activity or for atmospheric sampling. A detailed analysis of possible application of quadrotors ahs been provided in [59].

For applications like search and rescue quadrotors are used as multi-agent systems [27, 37, 47].

VIII. CONCLUSION

In this paper, the basics of a quadrotor UAV are reviewed and the various elements that concern the quadrotor UAV including different sensors, applications and their advantages are surveyed. It starts at the basic control structure and describes advanced applications that a quadrotor can be put to as well. The field of UAVs and specifically quadrotors has more areas to develop and improve. These areas have lead to major developments in automation and robotics.

The improvement in other technologies has given further leads in improving the design and computing power that can be associated with a quadrotor. Technologies like IC fabrication, chemical materials and programming are not the only fields that affect UAVs, various other fields add up to the improvement and hence the research in this field is never ending.

Further work on quadrotors coupled with fields like power systems, path planning and SLAM can result in a great number of applications in everyday life. Research in areas specific to the flight of a UAV is also important. For example, Figure 5 is a photograph taken during testing of a project that dealt with landing of a quadrotor on an oscillating surface [73]. Similarly research can also be done on other aspects like take-off and hover stabilization that would aid in finding new practical applications for quadrotors.

Fig. 5 Landing on oscillating surface

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